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# Modeling phenology of four grapevine cultivars (*Vitis vinifera* L.) in Mediterranean climate conditions

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ABSTRACT

A study was carried out to develop and validate models that simulate grapevine phenology of the cultivars Cabernet Sauvignon, Merlot, Chardonnay and Sauvignon Blanc growing under Mediterranean climate conditions. In this study, phenology models were developed using a monomolecular equation, where the dependent and independent variables were the Eichhorn and Lorenz (1977) phenological (ELP) scale modified by Coombe (1995) and growing degree days (GDD), respectively. From the beginning of budburst to harvest, measurements of ELP and GDD were collected weekly from 49 commercial vineyards located in the Maule Region, Chile (between 34° 40′ and 36° 33′ south latitude, 72° 38′ and 70° 18′ west longitude). The results showed significant nonlinear correlations between the GDD and ELP scale, with values of $R^2$ ranging between 0.95 and 0.98. Moreover, the validation indicated that the phenological models were able to predict the ELP scale with values of the root mean square error (RMSE), mean absolute error (MAE) and agreement index ($d_r$) raging between 1.6–3.0, 1.3–2.5 and 88–89%, respectively. Major disagreements were observed near the harvest stage (ELP = 40) which mainly depends on farm management.

## 1. Introduction

Climate and site characteristics, as well as the agronomical practices, affect the sustainable production of wine grapes (Hall et al., 2016). Commercial vineyards are distributed in a wide range of latitudes and climate, but this distribution may not be aligned with the climatic requirements of cultivars (Martínez-Lüscher et al., 2016). Thus, it is necessary to understand adequately how these factors influence grape production. Furthermore, the main viticulture areas are located in Mediterranean climate-type areas where the available water for irrigation is decreasing and temperatures are expected to increase due to climate change (Medrano et al., 2014). Using climate change scenarios, it is necessary to develop decision-making tools to optimize the use of water, fertilizers, pesticides and fuel in viticulture. Thus, modeling phenology is key since it allows growers to improve their knowledge about crop growth and developmental stages during the growing season. This information is the basis for improving the timing of pesticide applications as well as fertilization, irrigation and schedules for harvest operations (Verdugo-Vásquez et al., 2016).

Phenology is defined as the study of physiological events or growing plant stages that take place within a growing season in response to weather conditions (Gris et al., 2010). Moreover, phenology can be considered as an evaluation tool for measuring viticulture aptitude as a function of climatic behavior for crop growth (Jones and Davis, 2000). Studying and modeling phenology is widespread for all cultivated species, such as pome fruits (Darbyshire et al., 2013), peaches (Miranda et al., 2013), olives (Aguilera et al., 2014; Oteros et al., 2013), apricots (Andreini et al., 2014), and pistachios (Zhang et al., 2015) as well as grapevines (Caffarra and Eccel, 2011; Fila et al., 2014; Ortega-Farías et al., 2002; Parker, 2012; Verdugo-Vásquez et al., 2017; Zapata et al., 2015).

As a first approach to model phenology, McIntyre et al. (1982) and Faruqi et al. (1985) used chronological time with acceptable results. However, most of their studies about this topic were focused on temperature effects, which have the power to deeply modify the timing of plant development and phenological cycles (Darbyshire et al., 2013; Parker et al., 2013). Fila et al. (2014) described two family models used to estimate grapevine phenology: forcing type (F) and chilling and forcing type (CF). The first model uses the accumulation of forcing units with a fixed date throughout the computation of growing degree days (GDDs). These units are calculated using temperature sums above a threshold or base temperature to predict the phenology from budburst (Miranda et al., 2013). At the same time, the CF family model includes a description of the dormancy phase, and its ending date is the starting

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point of growing degree day accumulation (Fila et al., 2014). The F models have shown a good performance in comparison to the CF models in terms of predicting flowering and veraison events. The F models had root mean square errors (RMSE) of 5.4 and 8.0 days for flowering and veraison, respectively, in European vineyards (Parker et al., 2011). These models have presented better estimations for budburst (Hlaszny et al., 2012) and even for flowering and veraison (Caffarra and Eccel, 2010), although they are more susceptible to overestimations because of their higher complexities (Fila et al., 2014).

GDD are usually calculated by the method proposed by Amerine and Winkler (1944). This equation computes the GDD by the subtraction of a base temperature threshold from the daily mean temperature. However, the equation does not take into account the detrimental effect of high temperatures on plant cycles. This weakness is remedied using models that consider lower and upper thresholds to delimit the positive effect zone of temperature on plants. Good examples of these models are the simple triangle (Lindsey and Newman, 1956), simple sine (Baskerville and Emin, 1969) or normal and simple logistic (Rodríguez Caicedo et al., 2012) models. Additionally, the process of modeling phenology requires clear and universal information to correctly describe the growing evolution of the vineyard. Thus, an accepted scale is the Eichhorn and Lorenz (1977) phenological (ELP) scale modified by Coombe (1995), which covers 22 stages from "winter bud" to "end of leaf fall", using 47 numbers to clearly identify each developmental stage (Table 2).

Despite the available information in the literature, it is necessary to use a model that is able to simulate adequately vine phenology under different management types that incorporate the main climatic characteristics where the vineyards are located. Then, the objective of this research was to develop and validate phenological models to predict the ELP scale of the cultivars Cabernet Sauvignon, Merlot, Chardonnay and Sauvignon Blanc grown under Mediterranean climate conditions.

## 2. Materials and methods

### 2.1. Study area

This study was carried out in the provinces of Cauquenes, Linares and Talca, located in the Maule Region, Chile (between 34° 40′ and 36° 33′ south latitude, 72° 38′ and 70° 18′ west longitude). The 49 vineyard plots that were used to collect the climatic and phenological data are shown in Fig. 1. Plot information such as location, date of planting, area, spacing, and training system is presented in Table A1 in Appendix A. The studied cultivars were Cabernet Sauvignon, Merlot, Chardonnay and Sauvignon Blanc. Additionally, the study zone has a Mediterranean climate, presenting a maximum mean temperature of 26.9 °C in January, a minimum mean temperature of 3.9 °C in July, and an annual mean rainfall of approximately 680 mm. Approximately 80% of the total rainfall is concentrated in winter, while 2.2% occurs in the hot and dry summers between December and February. In the Maule region, accumulated values of GDD range between 1600 and 1800 °C day$^{-1}$ during the growing seasons.

### 2.2. Model description

The modeling of grapevine phenology was based on the relationship between the ELP scale and GDD. The ELP scale developed by Eichhorn and Lorenz (1977) and modified by Coombe (1995) was used in this study (Table 1). Values of GDD were calculated by the simple sine model that assumes a sinusoidal behavior of daytime variation of temperatures (Baskerville and Emin, 1969).

For the simple sine model, the thresholds used were 10 °C for the base temperature ($T_b$) and 35 °C for the upper temperature limit ($T_u$) (Buttrose and Hale, 1973). Then, GDD were calculated according to the following equations:

a) If $Tx < T_b$, then

$$GDD = 0 \tag{1}$$

- If $Tn < T_b$ and $T_b < Tx < T_u$, then

$$GDD= \frac{1}{\pi}\left[\left(\frac{Tx+Tn}{2} - T_b\right)\cdot\left(\frac{\pi}{2} - \theta_1\right) + \alpha\cdot Cos(\theta_1)\right] \tag{2}$$

- If $Tn > T_b$ and$T_b < Tx < T_u$, then

$$GDD= \frac{Tx+Tn}{2} - T_b \tag{3}$$

- If $Tn > T_u$ and $Tx > T_u$, then

$$GDD= \frac{T_u - T_b}{2} \tag{4}$$

- If $Tn < T_b$ and$Tx > T_u$, then

$$GDD= \frac{1}{\pi}\left[\left(\frac{Tx+Tn}{2} - T_b\right)\cdot(\theta_2 - \theta_1) + \alpha[Cos(\theta_1) - Cos(\theta_2)] + (T_u - T_b)\cdot\left(\frac{\pi}{2} - \theta_2\right)\right] \tag{5}$$

where Tn and Tx are the daily minimum and maximum temperatures, respectively, while $\theta_1$, $\theta_2$ and $\alpha$ values were calculated using the following equations:

$$\theta_1 = Arcsin\left[\frac{T_b - \frac{Tx+Tn}{2}}{\alpha}\right] \tag{6}$$

$$\alpha= \frac{Tx- Tn}{2} \tag{7}$$

$$\theta_2 = Arcsin\left[\frac{T_u - \frac{Tx+Tn}{2}}{\alpha}\right] \tag{8}$$

To obtain the values of ELP scale, phenological measurements were performed weekly from the beginning of budburst to harvest for each season. Then, the estimation of the ELP scale was based on the monomolecular model (Ortega-Farías et al., 2002; Verdugo-Vásquez et al., 2017):

$$ELP_i = ELP_f - \delta e^{-\beta\bullet GDD_i} \tag{9}$$

where $ELP_i$ is the number of the EPL scale, $ELP_f$ is number of the last phenological stage and $GDD_i$ is the accumulated values of growing degree days (°C). and $\beta$ are empirical constants.

### 2.3. Statistical analysis

For model development, a regression analysis between the $ELP_i$ and $GDD_i$ was carried out using a data set collected during the 1999–2000 and 2000–2001 growing seasons. In this case, the empirical coefficients $\beta$ and $\delta$ were estimated for each cultivar. To evaluate the goodness of fit of the phenological model, the coefficient of determination ($R^2$) was estimated for each cultivar.

For model validation, a comparison between the observed and estimated values of the $ELP_i$ was carried out using the root mean square error (RMSE), mean absolute error (MAE) and the index of model performance ($d_r$). Additionally, the ratio of the observed and estimated values ($r_{oe}$) was computed as the slope of the linear regression between them. Finally, the data set of GDD and the ELP scale to validate each

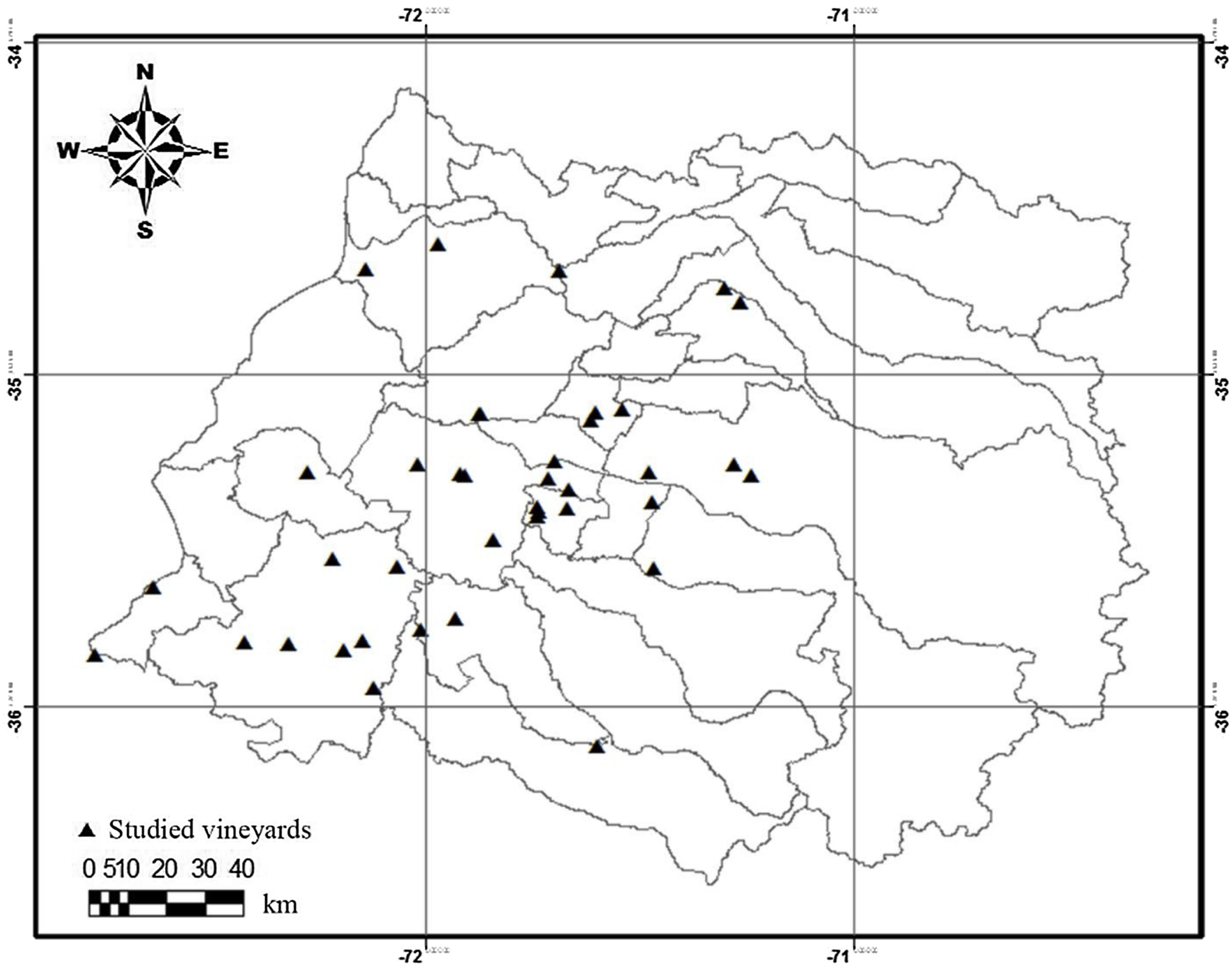


**Fig. 1.** Distribution of vineyard plots in the area of study.

**Table 1**
Summary of the phenological scale of Eichhorn and Lorenz (1977) modified by Coombe (1995).

| Phenological scale (ELP) | Phenological stage |
|---|---|
| 1 | Winter bud |
| 3 | Wooly bud – brown wool visible |
| 7 | First leaf separated from shoot tip |
| 9 | 2 to 3 leaves separated; shoots 2-4 cm long |
| 12 | 5 leaves separated; shoots approximately 10 cm long; inflorescence clear |
| 15 | 8 leaves separated, shoots elongating rapidly; single flowers in compact groups |
| 17 | 12 leaves separated; inflorescence well developed; single flowers separated |
| 19 | Approximately 16 leaves separated; beginning of flowering |
| 21 | 30% caps off |
| 23 | 17-20 leaves separated; 50% caps off, full bloom |
| 25 | 80% caps off |
| 27 | Setting; young berries enlarging (> 2 mm of diam), bunches at right angles to stem |
| 29 | Berries pepper-corn size (4 mm diam.); bunches tending downwards |
| 31 | Berries pea-size (7 mm de diam) |
| 33 | Berries still hard and green |
| 35 | Berries begin to color and enlarge: veraison |
| 38 | Berries harvest-ripe (22 ºBrix) |

**Table 2**
Empirical parameters of the exponential model to estimate grapevine a phenology scale for each cultivar and local area.

| Cultivar | Local area | $\hat{\beta}$ | $\hat{\delta}$ | $R^2$ |
|---|---|---|---|---|
| Cabernet Sauvignon | San Javier- Villa Alegre | 0.0021 | 33.59 | 0.97 |
| | Cauquenes-Parral | 0.0019 | 36.57 | 0.97 |
| | Talca -San Clemente | 0.0017 | 34.55 | 0.97 |
| | **Average** | **0.0019** | **35.05** | **0.97** |
| Merlot | Talca-San Clemente-Maule | 0.0019 | 35.51 | 0.96 |
| | San Javier - Villa Alegre | 0.0022 | 34.60 | 0.96 |
| | **Average** | **0.0021** | **35.52** | **0.96** |
| Chardonnay | Cauquenes | 0.0019 | 36.20 | 0.98 |
| | San Javier | 0.0021 | 32.47 | 0.95 |
| | Talca | 0.0018 | 34.78 | 0.97 |
| | **Average** | **0.0020** | **34.38** | **0.97** |
| Sauvignon Blanc | San Javier | 0.0022 | 36.92 | 0.98 |
| | Talca | 0.0019 | 36.79 | 0.96 |
| | **Average** | **0.0020** | **37.12** | **0.97** |

model was obtained during 2001–2002 growing season. Values of RMSE, MAE and $d_r$ were calculated as follows:

$$RMSE= \sqrt{\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{n}} \tag{10}$$

$$MAE= \frac{\sum_{i=1}^{n} |O_i - P_i|}{n} \tag{11}$$

$$d_r = \begin{cases} 1 - \dfrac{\sum_{i=1}^{n} |P_i - O_i|}{2\sum_{i=1}^{n} |O_i - \bar{O}|} \text{ if } \sum_{i=1}^{n} |P_i - O_i| \le 2\sum_{i=1}^{n} |O_i - \bar{O}| \\ \dfrac{2\sum_{i=1}^{n} |O_i - \bar{O}|}{\sum_{i=1}^{n} |P_i - O_i|} - 1 \text{ if } \sum_{i=1}^{n} |P_i - O_i| > 2\sum_{i=1}^{n} |O_i - \bar{O}| \end{cases} \quad (12)$$

where $P_i$ and $O_i$ are the predicted and observed values of the ELP scale, respectively, and $\bar{O}$ is the average of observed values.

## 3. Results and discussion

In this study, cv. Chardonnay needed an average of 1434 GDD for the first season and 1632 GDD for the second one. The cv. Cabernet Sauvignon required 1582 and 1731 GDD for the first and second seasons, respectively. These ranges are similar to those observed by Verdugo-Vásquez et al. (2016) who indicated a thermal accumulation between 1,385-1,523 GDD for cv. Chardonnay and 1,526-1,640 GDD for cv. Cabernet Sauvignon in the Maule Region. Also, the cv. Merlot required between 1,521-1731 GDD for reaching harvest. These values were higher than the average of 1200 GDD found by Gris et al. (2010) in the San Joaquin Valley (Southern Brazil) for a commercial vineyard training on a vertical shoot positioning trellis system. Finally, Villaseca et al. (1986) reported 1486 and 1177 GDD to reach harvest for Cabernet Sauvignon and Sauvignon Blanc, respectively.

### *3.1. Model development*

The results showed a significant nonlinear correlation between GDD and the ELP scale, with values of $R^2$ ranging between 0.95-0.98 (Table 2). The values of $\hat{\beta}$ were between 0.0017-0.0022 for the four cultivars, where the highest and lowest values were observed for Sauvignon Blanc and Cabernet Sauvignon, respectively. This range is lower than that found by Verdugo-Vásquez et al. (2017) for table grapes ($0.003167 < \beta < 0.0042$), but it was similar to the range reported by Ortega-Farías et al. (2002) and Fernández-González et al. (2013) for vineyard cultivars such as Cabernet Sauvignon, Chardonnay, Treixadura and Godello. Finally, the Table 2 indicates that $\hat{\delta}$ ranged between 32.5–36.9 with maximum and minimum values for Sauvignon Blanc and Chardonnay, respectively.

Fig. 2 shows that the monomolecular function (continuous line) appropriately represents the phenological progress regardless of locality or cultivar. Additionally, the concentration of observed values on the continuous line confirm the high correlations between the ELP scale and GDD suggesting that phenological evolution is thermal accumulation-dependent. However, major disagreements could be observed near the harvest stage (ELP 40) showing similar problems to those found by Ortega-Farías et al. (2002). An analysis of the main phenological stages (Table B1 in Appendix B) showed that the RMSE ranged between 13–32 days for the harvest period with the lowest and highest values for cultivars Cabernet Sauvignon and Sauvignon Blanc, respectively. At veraison, the RMSE ranged between 8 days for Sauvignon Blanc and 11 days for cv Chardonnay.

**Table 3**
Validation of the models to estimate the Eichhorn and Lorenz phenological scale for each cultivar using the root mean square error (RMSE), mean absolute error (MAE) and agreement index ($d_r$).

| Cultivar | RMSE (phenological stages) | MAE (phenological stages) | $d_r$ (%) | Slope |
|---|---|---|---|---|
| Cabernet Sauvignon | 1.6 | 1.3 | 93 | 1.06 |
| Chardonnay | 2.3 | 1.6 | 92 | 1.08 |
| Merlot | 2.1 | 1.4 | 93 | 1.04 |
| Sauvignon Blanc | 3.0 | 2.5 | 88 | 1.02 |

### *3.2. Model validation*

The model validation indicated that the phenological models were able to predict the ELP scale with RMSE, MAE and $d_r$ ranging between 1.6–3.0, 1.3–2.5 and 88–89%, respectively (Table 3 and Fig. 3). The models also estimated the day of occurrence of the whole phenological period with RMSE and MAE ranging between 10.9–12.0 and 8.3–9.1 days, respectively, and $d_r$ = 94% (Table 4). This result is similar to that indicated by Zapata et al. (2015) who obtained a RMSE and $d_r$ ranging between 6.1–10.8 days and 57–76%, respectively, for the cultivars Cabernet Sauvignon, Merlot and Chardonnay. In addition, Parker et al. (2011) reported a RMSE between 1.8–4.7 and $d_r$ between 46–77% for the cultivars Cabernet Sauvignon, Merlot, Chardonnay and Sauvignon Blanc.

The good performance of the proposed model under Mediterranean conditions could lead to designing suitable strategies to adapt to the effects of climate change on vineyards. However, one of the main limitations of this model is selecting the appropriate values of the lower

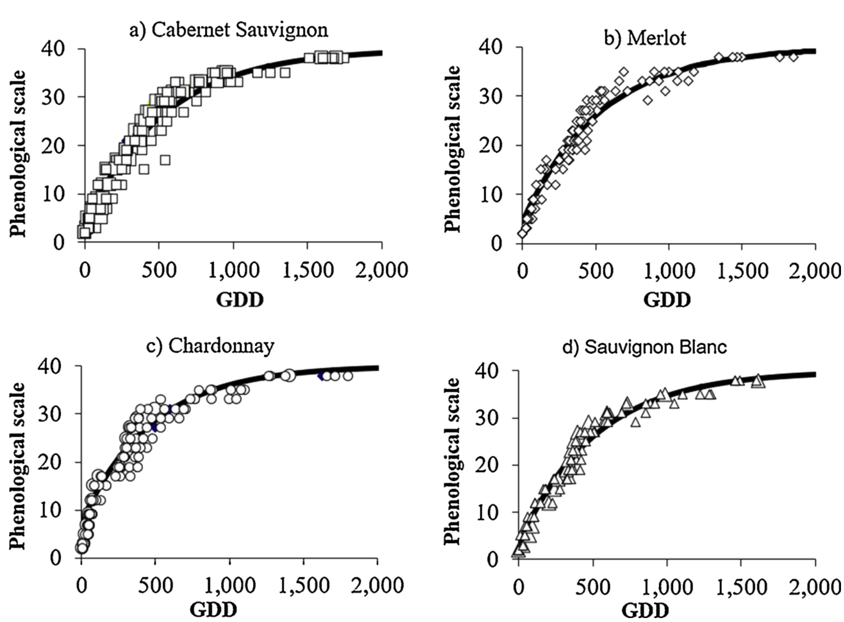

**Fig. 2.** Exponential models to estimate grapevine phenological scales using growing degree days (GDD).

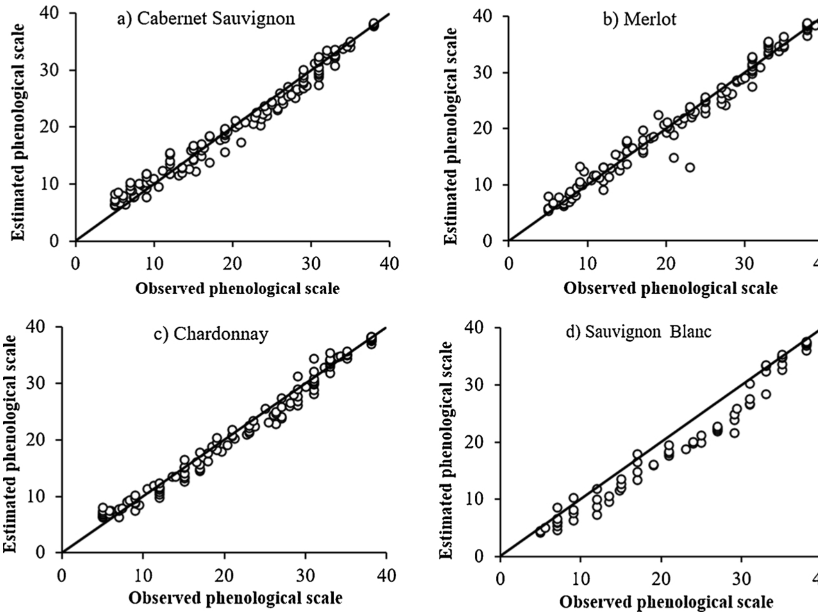


**Fig. 3.** Comparison between estimated and observed values of a grapevine phenological scale.

**Table 4**
Validation of the models to estimate the occurrence of the grapevine phenological stages for each cultivar using the root mean square error (RMSE), mean absolute error (MAE), agreement index ($d_r$) and the ratio of observed and estimated values ($r_{oe}$).

| Cultivar | RMSE (days) | MAE (days) | $d_r$ (%) | $r_{oe}$ |
|---|---|---|---|---|
| Cabernet Sauvignon | 10.9 | 8.6 | 94 | 0.99 |
| Chardonnay | 12.0 | 9.1 | 94 | 0.99 |
| Merlot | 10.9 | 8.3 | 94 | 1.02 |
| Sauvignon Blanc | 11.9 | 8.5 | 94 | 1.01 |

and upper thresholds for the calculation of the GDD for each phenological stage. Molitor et al. (2014) suggested lower and upper temperatures equal to 5 and 22 °C, respectively, which are lower than those used in this study ($T_b$ = 10° and $T_u$ = 35 °C).

The Table 5 shows the observed and estimated GDD to reach the main phenological stages of flowering (23), setting (27), veraison (35) and harvest (38). The harvest was the critical stage for red cultivars, where the maximum difference between the observed and estimated GDD was obtained, while white cultivars presented a good fit in four stages even though both observed and estimated values seem to be larger than typical values for these cultivars. In this study, the thermal accumulation estimated for veraison was 1,025, 934 and 964 GDD for Cabernet Sauvignon, Merlot and Chardonnay, respectively. These values are similar to those reported by Zapata et al. (2015) for Cabernet Sauvignon (GDD = 962 °C), Merlot (GDD = 997 °C) and Chardonnay (GDD = 952 °C). Also, the values of GDD calculated in this research (Table 5) are greater than those indicated by the Amerine and Winkler (1944) approach.

The advantages to using these models correspond to the unique adjustment to the developmental rate parameter ($\beta$) and provide a dynamical characterization of the GDD accumulation, which is in function of the daily behavior of temperatures.

This research developed and validated a nonlinear relationship between GDD and the ELP scale, considering that the temperature can deeply modify the timing of a vine. In addition, climatic conditions for both the development and validation were very similar. This scenario indicates that the simulation of phenological stages (ELP) using the proposed models applied under different climatic conditions to those observed in this study might not be very accurate. For practical application, therefore, the proposed models need to be validated for vineyards growing under a wider range of atmospheric conditions.

Another limitation to this study is that the phenological models need the date of occurrence of budburst as input for starting the accumulation of GDD, which may produce errors in GDD estimations because budburst is determined by farmer observations. To avoid this limitation, it could be necessary to implement a submodel to predict the date of occurrence of budburst using chilling hours and heat accumulation (García de Cortázar-Atauri et al., 2009; Molitor et al., 2014). Thus, García de Cortázar-Atauri et al. (2009) evaluated an agro-meteorological model for simulating grapevine budburst occurrence using extreme daily temperatures and hourly temperatures to estimate the dormancy, postdormancy and dormancy break periods. However, their results showed that the calculation of the dormancy period was not as

**Table 5**
Observed (O) and estimated (E) growing degrees days (GDD) to reach the main phenological stages according to the Lorenz et al. (1995) phenological scale modified by Coombe (1995).

| Phenological stage | Cabernet Sauvignon | | Merlot | | Chardonnay | | Sauvignon Blanc | |
|---|---|---|---|---|---|---|---|---|
| | O | E | O | E | O | E | O | E |
| Flowering (23) | 399 | 381 | 344 | 351 | 381 | 352 | 394 | 390 |
| Setting (27) | 487 | 522 | 409 | 479 | 444 | 486 | 459 | 525 |
| Veraison (35) | 1,036 | 1,025 | 864 | 934 | 1,000 | 964 | 1,035 | 1,002 |
| Harvest (38) | 1,645 | 1,507 | 1,485 | 1,370 | 1,467 | 1,422 | 1,499 | 1,461 |

critical as the base temperature to calculate GDD and cultivar specificity for improving model performance under current climate conditions.

## 4. Conclusions

The model developed in this research was able to characterize adequately a phenological scale of grapevines considering different cultivars with variable conditions within the Maule Region, showing estimates of the ELP scale with RMSE, MAE and $d_r$ values ranging from 1.6 to 3.0, 1.3–2.5 and 88–89%, respectively. Based on these results, a monomolecular model can be used under Mediterranean climate conditions to estimate phenological stages of Cabernet Sauvignon, Merlot, Chardonnay and Sauvignon Blanc as a function of GDD. Furthermore, an improvement that could be implemented is the use of specific temperature response ratios for every cultivar as well as an in-depth analysis of the chilling requirements related to adequate knowledge about budburst occurrence. Finally, it would be interesting to test the model in other localities with similar climatic conditions to evaluate the stability of the predictions.

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## Appendix A

**Table A1**
Vineyard plot descriptions.

| Cultivar | Location | Date of planting | Area (ha) | Spacing (m x m) | Trellis/t raining system |
|---|---|---|---|---|---|
| Cabernet Sauvignon | Cauquenes | 1977 | 2.4 | 3.0 × 2.5 | Genovese overhead |
| | | 1977 | 2.5 | | |
| | | 1986 | 0.5 | 3.0 × 1.5 | Double crosspieces |
| | | 1987 | 0.9 | 3.0 × 2.0 | Single curtain |
| | | 1990 | 1.5 | 3.5 × 1.0 | High Californian curtain |
| | | 1994 | 1.3 | 3.5 × 0.5 | Double crosspieces |
| | | 1997 | 3.8 | 4.0 × 0.5 | Lyra |
| | Pencahue | 1994 | 2.1 | 2.8 × 1.6 | High curtain |
| | | 1995 | 1.6 | 2.8 × 1.0 | |
| | Retiro | 1995 | 4.8 | 2.8 × 1.4 | Single curtain |
| | | 1996 | 4.3 | | |
| | Río Claro | 1986 | 2.5 | 3.5 × 2.0 | High crosspieces |
| | | 1986 | 5.2 | | |
| | San Clemente | 1994 | 14.1 | 3.0 × 1.0 | Single curtain |
| | San Javier | N/I | 0.9 | 1.7 × 1.0 | Single curtain |
| | | 1985 | 6.5 | 3.0 × 1.2 | Crosspieces |
| | | 1993 | 3.7 | 2.9 × 1.5 | Single curtain |
| | | 1994 | 2.6 | 4.0 × 4.0 | Spanish overhead |
| | Talca | 1955 | 4.2 | 4.0 × 2.0 | Spanish overhead |
| | | 1990 | 1.6 | 2.9 × 0.9 | Scott-Henry |
| | | 1995 | 6.3 | 3.0 × 1.0 | Single curtain |
| | Villa Alegre | 1989 | 2.6 | 2.0 × 1.0 | Single curtain |
| | | 1993 | 4.2 | 4.0 × 4.0 | Spanish overhead |
| Merlot | Maule | 1996 | 8.3 | 2.5 × 1.2 | Single curtain |
| | Pencahue | 1996 | 2.9 | 3.0 × 1.2 | High curtain |
| | Río Claro | 1993 | 0.5 | 3.0 × 1.5 | Low curtain |
| | San Clemente | 1993 | 7.5 | 3.0 × 1.0 | Single curtain |
| | San Javier | N/I | 3.1 | 2.4 × 1.2 | Single curtain |
| | | 1990 | 5.6 | 2.6 × 1.0 | |
| | | N/I | 1.3 | 3.0 × 1.7 | |
| | Talca | 1992 | 4.5 | 2.9 × 1.0 | Scott-Henry |
| Chardonnay | Cauquenes | 1986 | 1.2 | 3.0 × 1.2 | N/I |
| | | 1988 | 1.2 | 2.5 × 0.8 | Lyra |
| | | 1992 | 1.1 | 3.5 × 1.0 | High Californian curtain |
| | | 1993 | 2.5 | 3.5 × 0.5 | Double crosspieces |
| | | 1993 | 1.4 | 4.0 × 0.4 | Lyra |
| | | 1994 | 0.5 | 3.0 × 1.4 | Genovese overhead |
| | Empedrado | 1989 | 3.1 | 3.5 × 1.1 | Crosspieces |
| | San Javier | 1985 | 2.8 | 3.0 × 1.0 | N/I |
| | | N/I | 0.8 | 2.4 × 1.0 | Single curtain |
| | | N/I | 4.1 | | |
| | | 1992 | 2.4 | 3.0 × 3.0 | Spanish overhead |
| | Talca | 1990 | 1.2 | 2.9 × 0.9 | Scott-Henry |
| Sauvignon Blanc | Cauquenes | 1969 | 1.6 | 2.5 × 1.0 | Single curtain |
| | Maule | 1939 | 6.1 | 2.9 × 1.2 | Single curtain |
| | Talca | 1942 | 4.5 | 3.2 × 1.2 | Single curtain |
| | San Javier | 1986 | 3.7 | 3.0 × 1.5 | High crosspieces |
| | | 1993 | 3.1 | 2.4 × 1.0 | Single curtain |

N/I corresponds to no information.

## Appendix B

**Table B1**
Statistical analysis of the estimated occurrence dates of the main phenological stages using the root mean square error (RMSE), mean absolute error (MAE) and the index of agreement ($d_r$).

| Cultivar | Statistic | Flowering | Setting | Veraison | Harvest |
|---|---|---|---|---|---|
| Cabernet Sauvignon | RMSE (days) | 5 | 7 | 9 | 13 |
| | MAE (days) | 4 | 5 | 8 | 12 |
| | $d_r$ (%) | 97 | 97 | 98 | 97 |
| Merlot | RMSE (days) | 10 | 14 | 9 | 19 |
| | MAE (days) | 6 | 9 | 7 | 15 |
| | $d_r$ (%) | 94 | 93 | 98 | 96 |
| Chardonnay | RMSE (days) | 7 | 13 | 11 | 29 |
| | MAE (days) | 6 | 11 | 10 | 27 |
| | $d_r$ (%) | 96 | 93 | 98 | 0.93 |
| Sauvignon Blanc | RMSE (days) | 8 | 9 | 8 | 32 |
| | MAE (days) | 8 | 8 | 6 | 31 |
| | $d_r$ (%) | 94 | 95 | 99 | 92 |

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